SMART PASSIVE COOLING SYSTEMS FOR SUSTAINABLE ARCHITECTURE IN DEVELOPING COUNTRIES: USING THE GAP TO BRIDGE THE GAP

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Summary

Most of the research in architectural sustainability has been centered on developed countries because these consume the most energy and have the most resources, but sustainable architecture is also important in less developed countries. As developed countries implement conservation measures and the population of less developed countries increases, these will approach or surpass the consumption levels of developed countries. Less developed countries also offer opportunities to implement alternative low energy strategies. Passive cooling systems have already been in use for hundreds of years in vernacular buildings and use a fraction of the energy used by conventional mechanical systems. A prototype microcomputer-controlled thermostat can further improve their performance by monitoring outdoor conditions and adjusting the systems accordingly. This will ultimately lead to a building that can adapt to daily and seasonal rhythms, with a strong connection with the environment. This thermostat has been tested with radiant, indirect evaporative, and ventilative cooling systems, in the last case also combined with smart window blinds. The ventilative cooling system and equations derived from the experimental work that permit to calculate internal maximum temperature as a function of outdoor maximum temperature, daily swing, window area, and thermal mass, are described in this paper.

1. Introduction

Buildings account for about 50% of the energy consumed in developed countries, most of which still comes from non renewable sources. The environmental impact due to the process of extraction, production and transportation combined with its ever increasing cost have contributed to make energy related issues an ever more important issue within the broad context of sustainable architecture.

In most countries there are excellent examples of vernacular architecture and many contemporary architects have also embraced some of the principles of ecological design, creating interesting examples of low energy buildings adapted to the climate.

Passive heating systems store and distribute solar energy without the need of complex controllers for its distribution, raising indoor temperatures above outdoor values. Passive cooling systems transfer incident energy to natural energetic deposits, or heat sinks, such as the air, the upper atmosphere, water and earth, lowering the temperature of the air inside the building. When passive heating or cooling systems are incorporated in building design, energy consumption for heating or cooling can be greatly reduced and in some cases eliminated altogether, reducing nonrenewable energy consumption and global pollution, so that the whole planet benefits.

2. Passive Cooling Systems in Developing Countries

2.1. Importance of Sustainable Principles in Developing Countries.

Most of the measures to reduce energy consumption and implement sustainable design concepts are directed to improve the performance of buildings in developed countries because these countries are the main consumers of energy. In these countries mechanical heating and cooling are standard in most buildings, except in the buildings of the very poor. On the other hand, in most developing countries, the cities are economically and socially divided in a formal and an informal sector, and there are two distinct types of buildings with different physical representations and qualities. The buildings in the informal sector are usually built without codes and while the buildings of the formal sector are built follwoing different codes, there is usually no energy code. Thermal conditions inside most unconditioned dwellings in these countries are usually worse than outdoors, and those families that can afford mechanical cooling systems to achieve comfort spend a large portion of their income in electrical bills.

Energy consumption is usually linked to economic growth and the development level of a country, so its consumption is unevenly distributed in the world. Developed market economies, which constitute one fifth of the world's population, consume almost 60 % of the world's primary energy. But this proportion is changing and as a consequence of development and the rapid replacement of traditional energy sources by commercial (mainly fossil) sources, some regions of developing countries have consumption patterns similar to those of developed market economies. To make matters worse, the energy needed to power these buildings is sometimes generated by old, inefficient and polluting facilities.

Population in less developed countries is growing faster than in more developed countries. While developed countries grow at an average rate of 0.4% per year, less developed countries grow at a rate of 1.4% and the least developed countries at a rate of about 2.4% per year. Even by simple population growth their share in world energy consumption will probably increase.

Development differences inside countries also create differences in life quality, with different levels of per capita energy consumption in different parts of the country, which in some cases are even higher than that of more developed countries. As the quality of life improves in these countries and developed countries implement conservation measures, less developed countries will approach the consumption levels of developed countries.

2.2. Implementation of Passive Cooling Systems in Developing Countries

While societies of developing countries have many needs, they are also evolving rapidly. Families in these societies are usually very open to changes and opportunities that will help them live better. They struggle, but with hard work many have the opportunity to prosper and improve their quality of life.

Since conventional cooling and heating systems are not widely used in developing countries, there is an opportunity to implement a different option that would provide sufficient cooling at a fraction of the expense of conventional systems, while being respectful of the outdoor environment and socially acceptable. Passive cooling systems offer this opportunity.

Passive cooling systems have lower initial and operating costs than air conditioners, which are expensive and out of reach of low income and even many middle income families in less developed countries. Even families that can afford to buy air conditioners, sometimes cannot provide maintenance for them or even turn them on when they need to.

Because of their simple design, passive cooling systems can be built at lower costs and using local labor and resources, generating income for local entrepreneurs, that stays in the community and contributes to local development. There is also a haptic quality about the use of Passive Cooling Systems, the dweller knows what part of the house is operating to achieve comfort and can see and feel the effect of the system as it works to harness the natural forces and cool the house. And since passive cooling systems rely on building design and materials to control natural forces, they help to establish a closer connection between the dwellers and the environment through the building, ultimately helping to better connect with nature's rhythms. If passive systems are added in existing buildings as the population wishes to improve their life quality, energy consumption will increase very little, while thermal comfort will improve substantially. If passive cooling systems are well integrated and generally accepted by the population, it would be an important step to create a more sustainable architecture in developing countries.

Three passive cooling systems were tested in the Energy Laboratory of the Department of Architecture at the University of California Los Angeles: ventilative cooling, radiant cooling and indirect evaporative cooling. Because of space limitations only results of the experiments with ventilative cooling are presented in this paper.

3. Smart Nocturnal Ventilative Cooling with Different Window Dimensions

Architectural science has perfected the calculation techniques involved in the design of passive cooling systems so that it is now possible to design them with more precision. Making these systems "smart" by using a prototype microcomputer-controlled thermostat (La Roche & Milne, 2002, 2003, 2004) should improve their performance even more. This thermostat was designed and developed to operate systems that would provide thermal comfort harnessing the resources available in the environment. It was tested extensively on the ventilative and shading systems. This section describes experimental results using the smart controller to operate a fan and provide ventilative cooling as needed. The effect of solar radiation through south facing windows is considered by changing the window dimensions.

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates. Night ventilation reduces internal maximum temperatures, peak cooling loads, and overall energy consumption and has been well documented (Cook, 1989) (Givoni, 1994) (Stein, Reynolds 1992). (Santamouris, Asimakopoulos, 1996) (Allard, Santamouris, 1998).

The applicability of nocturnal ventilative cooling is limited to a certain range of conditions (Givoni, 1994) which are a function of the needs of the occupants and climatic conditions. Occupants affect decisions such as opening or closing of the windows during the night and the desirable comfort levels. The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level, which determines the upper temperature limit of indoor comfort with still air or with air movement (Geros et al, 1999). Since the outdoor daily temperature swing increases as the air humidity is reduced, the humidity of the air is one of the practical determinants of the applicability of different ventilation strategies. Even though this strategy is usually not considered effective in warm humid climates, some authors (Machado, La Roche, 1999) (Szokolay, 2000) have explored the implementation of nocturnal ventilative cooling as a passive cooling option for buildings in warm humid climates. The performance of the smart controller for ventilative cooling could also be predicted in warm humid climates because the effect of the outdoor swing is accounted for in the equation to determine the maximum temperature. Using a smart controller improves the performance of the system because the fan operates precisely when it is needed.

3.1. Experimental System

The experimental system consists of a microprocessor controller connected to thermistors that measure temperature, a computer which contains the control programs and collects and stores experimental data and two test cells, the experimental cell and the control cell. These have a fan and damper that are adjusted depending on the need for cool air. In the experimental cell the maximum air change rate is 15 air changes per hour and the shade on the window can be completely open or completely closed. In the control cell there is a fixed infiltration rate of about 0.5 air changes per hour and there is no shade in the window (Fig. 1).

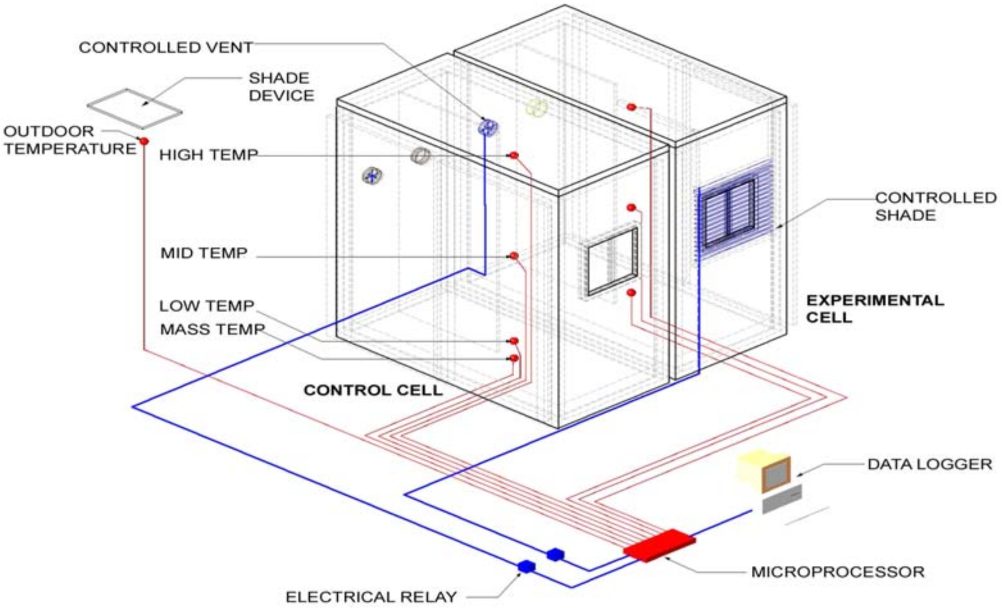

Figure 1 The experimental system

3.2. Results and Discussion

Various control strategies were tested in the summer of 2001 comparing different air change rates and values for comfort low and comfort high. Some of the series that tested these strategies are presented in table 1. The objective of all the strategies that were tested was to provide maximum cooling with outdoor air and achieve comfort with minimum energy consumption. Since both cells are built identically, performance could be evaluated by comparing the results of the experimental cell with the control cell.

Table 1 Some of the Tests Performed to Determine the Best Rule to Control the Air Change Rate

Series	Comfort Low (°C)	Comfort High (°C)	Maximum Air Changes per Hour
Basic Comfort	21.1	25.5	3.9
Reduced Comfort Low	18.3	25.5	3.9
Reads Mass Temperature	21.1	25.5	3.9
Increased air change rate	21.1	none	15
Higher air change rate & lower cmf low	15.6	none	15

The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell is indicated in equation (1). This is the rule that is used in the smart thermostat in all series and would be the rule to be used in thermostats in real buildings to achieve maximum cooling with ventilation.

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* fan ON else fan OFF (1)

Where:

t_o = temperature outside

t_i =temperature inside

C_{f_low}, = comfort low at 18.3 °C

C_{f_high} = Comfort high at 25.5 °C

Several tests were performed in the summers of 2002 and 2003 to explore the effects of modifying the amount of mass, the size of the window and the air change rate. The window size was modified from its full size position by also covering all or half of its surface with an opaque wall insulation panel. The different tests are shown in table 2.

Table 2 Tests Performed to Determine the Effects of Window Size, Mass and Air Change Rate

Series and Date	Experimental Cell
1. May 22, 2002	Window: 50%, Air Change: 0.7, Mass: 760 lbs brick
2. May 29, 2002	Window: 0%, Air Change: 0.7, Mass: 760 lbs brick
3. June 20, 2002	Window: 100%, Air Change: 0.7-3.9, Mass: 760 lbs. brick
4. July 15, 2003	Window: 50%, Air Change: 0.7-3.9, Mass: 760 lbs brick
5. June 11, 2002	Window: 0%, Air Change: 0.7-3.9, Mass: 760 lbs brick
6. August 17, 2002	Window: 0%, Air Change: 0.7-3.9, Mass: 1560 lbs brick
7. August 8, 2002	Window: 100%, Air Change: 0.7-3.9, Mass: 1560 lbs brick

Since in all series there was a correlation between the outdoor swing and the difference between the indoor and outdoor maximum temperatures, the Temperature Difference Ratio, TDR was used to analyze the data and develop the equations that would predict the performance of these systems. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations (La Roche & Givoni, 2002) (La Roche & Milne 2004). TDR is determined using the following equation:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \qquad (2)$$

Where:

TDR= Temperature Difference Ratio

T_{maxout}: Maximum temperature outside

T_{maxin}: Maximum temperature inside

T_{minout}: Minimum temperature inside

The numerator is the difference between the indoor maximum temperature and the outside maximum, and the denominator is the outdoor swing. In a naturally ventilated building the result of this division can't be higher than 1.0. The higher the value of the TDR, the better the cooling performance of the system. A higher value indicates that there is a larger temperature difference between outdoors and indoors and there is more cooling. The TDR concept normalizes the capacity to reduce the indoor maximum temperature as a function of the outdoor swing, due to differences in the setup.

Equations 3 and 4 predict the TDR as a function of south facing window to floor ratio in the control and experimental cells.

The predictive equation for the control test cell with a fixed infiltration rate of 0.7 air changes per hour is:

$$\text{TDR} = 20 - 1.8 * \text{SWFR} \qquad (3)$$

The predictive equation for the experimental test cell with the smart ventilation system and a maximum ventilation rate of 3.9 air changes per hour is:

$$\text{TDR} = 32 - 1.2 * \text{SWFR} \qquad (4)$$

In both:

TDR= Temperature Difference Ratio

SWFR = South Window to Floor Ratio

After TDR is calculated for a building using equations 3 and 4, it is possible to predict the indoor maximum temperature using equation 2 and solving for T_{maxin} . Outdoor maximum and minimum temperatures, or daily temperature swing, must be known.

$$T_{maxin} = T_{maxout} - [\text{TDR} * (T_{maxout} - T_{minout})] \qquad (2)$$

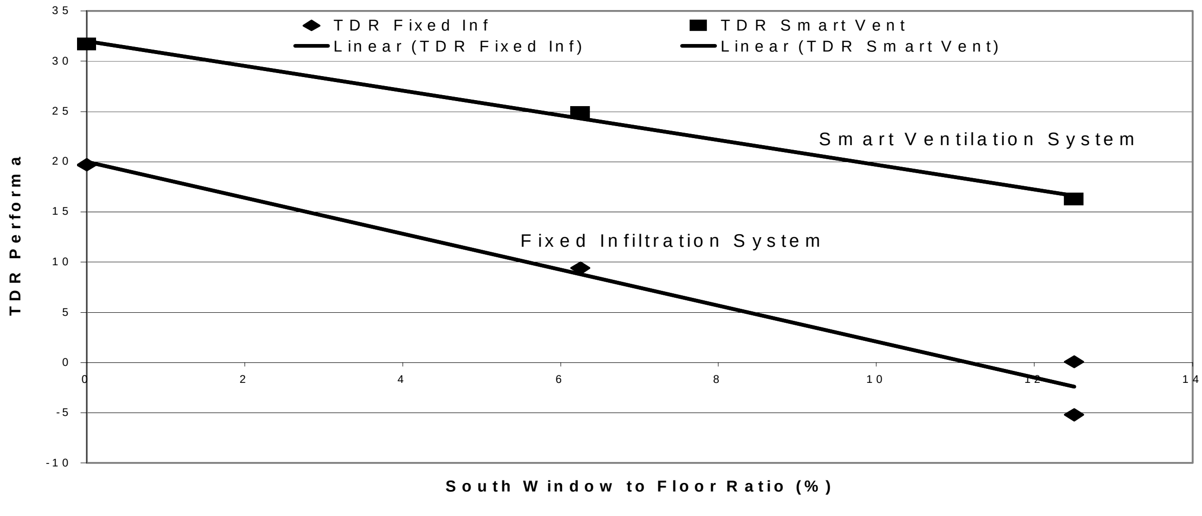

Figure 2 *TDR as a function of the south facing window to floor ratio.*

In both slopes for equations (3) and (4), as the south window to floor ratio increases, the TDR decreases. Larger unshaded south facing windows reduce the performance of a system with ventilative cooling. The slope for the smart ventilation system is about 12 TDR percentage points above the slope for the fixed controller system, indicating a better performance with the smart controller. When the south window to floor ratio is above 11.1% the conditions inside the control cell, with a fixed infiltration rate, would be worse than outdoors while with the smart controller the south window to floor area can reach 26.6% before the indoor temperature is higher than outside temperature. These equations could be used in buildings with lightweight walls, shaded north, east and west windows, and slab-on-grade construction to predict maximum temperatures with specific window sizes on the south orientation or to determine maximum dimensions for south facing windows that would achieve a specific indoor maximum temperature.

4. Smart Nocturnal Ventilative Cooling combined with Smart Shading

4.1. Experimental System

The same cells were also used to test smart ventilation combined with smart shading, instead of a fixed window size, and with different amounts of mass inside the test cell. The rule that is used to operate smart shade in this controller and tested in 2003 is:

If 70 F < t_i *then* Shade Down else Shade Up (5)

Eight series were tested. Four series had the blinds outside the window and four series had the blinds inside. Each of these four series had different amounts of mass inside the test cell equivalent to 75, 150, 225 and 300 kg/m^2. The control series always had the shade open and the fan off with a constant mass of 150 kg/m^2.

Table 1 Combined Smart Venting and Shading Series Tested

Series	Description
1. SHADE INSIDE & LOW MASS	Fan ON 0-15 Air changes Hour, Shade ON Inside, 75 kg/m^2
2. SHADE INSIDE & MED MASS	Fan ON 0-15 Air changes Hour, Shade ON Inside, 150 kg/m^2
3. SHADE INSIDE & MED-HIGH MASS	Fan ON 0-15 Air changes Hour, Shade ON Inside, 225 kg/m^2
4. SHADE INSIDE & HIGH MASS	Fan ON 0-15 Air changes Hour, Shade ON Inside, 300 kg/m^2
5. SHADE OUTSIDE & LOW MASS	Fan ON 0-15 Air changes Hour, Shade ON Outside, 75 kg/m^2
6. SHADE OUTSIDE & MEDIUM MASS	Fan ON 0-15 Air changes Hour, Shade ON Outside, 150 kg/m^2
7. SHADE OUTSIDE & MED-HIGH MASS	Fan ON 0-15 Air changes Hour, Shade ON Outside, 225 kg/m^2
8. SHADE OUTSIDE & HIGH MASS	Fan ON 0-15 Air changes Hour, Shade ON Outside, 300 kg/m^2

4.2. Results

Since sufficient correlation was found between the daily outdoor temperature swing and the daily TDR, the Temperature Difference Ratio (TDR) was again used to evaluate the performance of the different variables in these series. Predictive equations were developed to determine the maximum temperatures inside test cells with different mass.

The TDR is calculated for each day of the different series and averaged for each series. The eight series are plotted in figure 3, which correlates the amount of mass (kg/m2) in the floor slab with the TDR. One trendline is plotted for the series with the shade inside and another for the series with the shade outside, which has higher TDR values (Fig 3). The equations that predict the TDR as a function of the amount of mass are:

$$TDR_{shdout} = 0.0005 * Mass + 0.2398 \quad (7)$$

$$TDR_{shdin} = 0.0009 * Mass + 0.0194 \quad (8)$$

Where:

TDR_{shdout} = TDR with the shade outside

TDR_{shdin} = TDR with the shade inside

Mass = Floor slab mass kg/m^2

Equations (7) and (8), which are plotted in figure 3, predict TDR as a function of the amount of mass (in kg/m^2) in the slab. If TDR is known it is then, again, a simple matter to predict the indoor maximum temperature as a function of the daily swing and the amount of mass in the slab using equation (2). These equations can be used to predict indoor maximum temperature as a function of outdoor maximum temperature in well insulated buildings that have smart controllers for both ventilation and shading, either outside or inside the window.

The measured and predicted daily maximum temperatures in series 7 are shown as an example of the application of these equations. The difference between measured and predicted values is always less than ½ degree °C (Fig 4).

Applying the equation to Maracaibo, a city with a warm and humid climate in Venezuela, where the summer maximum average outdoor temperature is 32.8 C and the average daily swing is 9.2 C the maximum predicted temperature inside a building with 300 k/m2 of mass in the slab would be 29.21 C. If the relative humidity is 70% at this time of the day, thermal comfort can still be achieved with air movement. If we reduce the amount of mass to 75 k/m2, the maximum temperature inside the cell would be 30.2 C. Because of the small outdoor daily swing, the difference between the maximum temperatures with different amounts of mass is not notable. Nevertheless, it would be still possible to use a combination smart shading and venting system such as this one, even in warm humid climates.

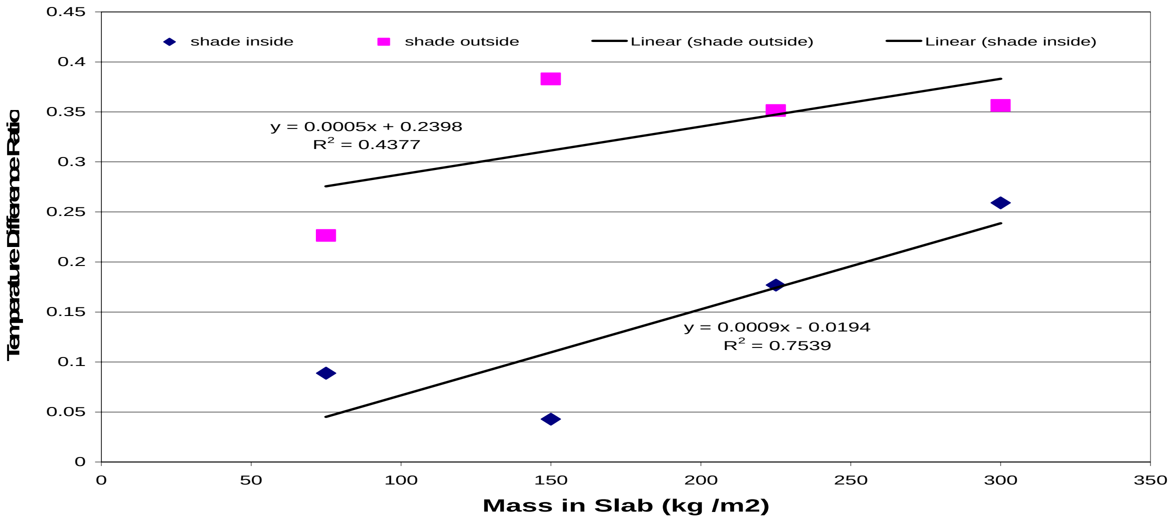

Figure 3 *Correlation between the floor mass and the TDR performance in the test cells with a smart ventilation and shading system.*

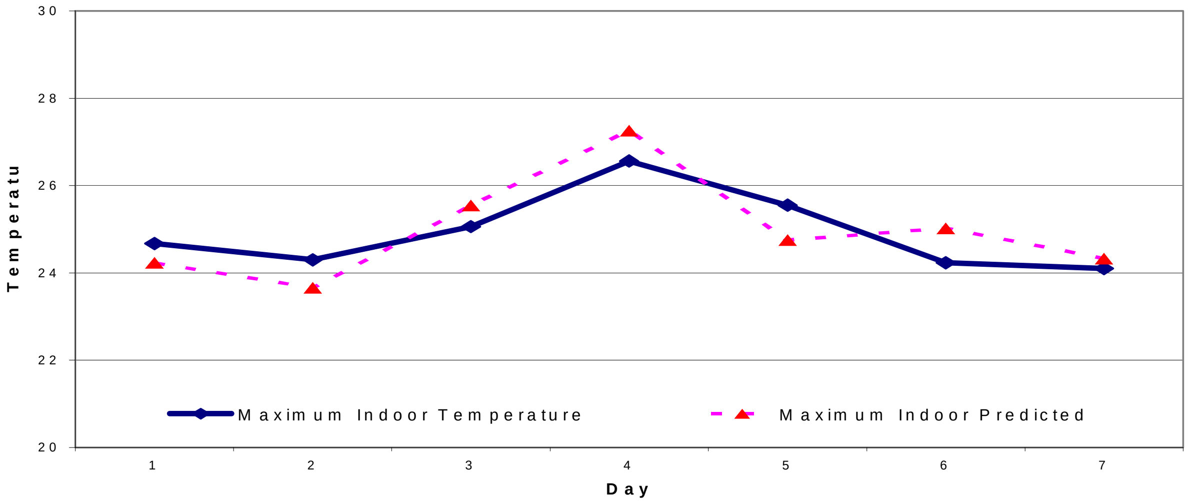

Figure 4 *Measured and predicted daily maximum average temperatures in the experimental cell in series 7.*

6. Conclusion

This paper demonstrates that when conditions are suitable, it is possible to use ventilative cooling with a smart thermostat to reduce the maximum temperature inside buildings in warm climates. Sets of equations have been developed to predict the indoor maximum temperature as a function of different variables, permitting to determine the applicability of different systems under different climates. These tests confirm that more mass with the blinds outside the window performed better than less mass with the blinds inside and a higher air change rate performs better than a lower air change rate.

Smart ventilative cooling requires only a fan and a thermostat and is much more affordable than conventional compressor based mechanical cooling systems. Furthermore, all passive cooling systems can be built with locally available materials and components as long as they don't affect the physics of the systems. Because of their low cost and possibility of integration with local technologies and materials, passive cooling systems are a viable option in less developed countries, helping to create buildings that are connected and adapted to regional climates. Appropriate architecture could help these countries develop in a sustainable manner that does not have to follow the same route of more developed countries that have built high energy buildings supported by a carbon based economy. Less developed countries could skip this stage and develop buildings that use appropriate, local and smart technology adapted to their specific physical and social environments. These buildings which are mostly located in warm climates, should be able to reduce heat gains from the outside, incorporating whenever possible lessons from local vernacular architecture and Passive Cooling Systems. As the families have the possibility to improve their quality of life they can implement passive cooling systems instead of conventional compressor cooling systems.

Creating a sustainable green building involves many design issues which are out of the scope of this paper, but if energy is saved and thermal comfort is improved inside the building, an important first step will have been taken. Furthermore nonrenewable energy consumption and global pollution would be reduced, so that the whole planet benefits. At the end all buildings should be sustainable, and passive cooling systems can help to achieve this sustainability.

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